Properties and Applications of Laser Generated X-Ray Sources

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ABSTRACT

The rapid development of laser technology and related progress in research using lasers is shifting the boundaries where laser based sources are preferred over other light sources particularly in the XUV and x-ray spectral region. Laser based sources have exceptional capability for short pulse and high brightness and with improvements in high repetition rate pulsed operation, such sources are also becoming more interesting for their average power capability. This study presents an evaluation of the current capabilities and near term future potential of laser based light sources and summarises, for the purpose of comparison, the characteristics and near term prospects of sources based on synchrotron radiation and free electron lasers. Conclusions are drawn on areas where the development of laser based sources is most promising and competitive in terms of applications potential.

Keywords: X-ray, Laser, Brightness

1. INTRODUCTION

Laser produced plasmas emit x-rays through a variety of processes. Where the source of the emission is collisions of thermal electrons with plasma ions the resulting line or continuum radiation can be categorised as thermal. In the limit of high opacity, the emission may be that of a Planckian black body. Laser produced plasmas also commonly have a minority of hot electrons arising from non-linear laser plasma interactions. These non-thermal electrons typically experience few collisions in the laser produced plasma and interact strongly with cold solid target material to induce K-alpha fluorescence and Bremsstrahlung emission.

At high intensities the laser EM wave can drive highly anharmonic motion of electrons which results in intense emission of very high harmonics in gases and from solid targets. X-ray lasing at XUV wavelengths can occur in an extended plasma column through amplified spontaneous emission yielding narrow bandwidth, high energy outputs in well collimated pulses. The process of Thomson scattering of laser light by free electrons is modified when the oscillation energy of the electron in the light wave becomes relativistic. The scattered frequency is upshifted and can reach the soft x-ray region where the emission becomes highly directional Larmor radiation. Relativistic frequency shifts to the x-ray region also occur in Thomson scattering of laser light from relativistic electron beams and such Thomson sources may produce collimated beams of rather hard x-rays. The characteristics of all these laser based sources are compared and discussed in the sections which follow. Comparisons between laser and synchrotron based x-ray sources are given within charts of peak and average brightness. The units of brightness are given by *photons s^{-1} mm^{-2} $mrad^2$ in 0.1% $\Delta\lambda/\lambda$* which is the preferred unit of characterisation for synchrotrons facilities. For convenience these units will be referred to as brightness units within the text.

2. LASER BASED X-RAY SOURCES

2.1 Thermal Sources
Thermal emission, into line or continuum radiation, is generated by the collisions of thermal electrons with plasma ions and dominates when the intensity of the laser driver exceeds the ionisation threshold at about 10^{15} W cm^{-2} and the $I\lambda^2$ [intensity x (wavelength)^2] is below about 10^{15} W cm^{-2} μm^2. Table top sub-Joule laser systems are capable of accessing this intensity range at kHz repetition rates and can produce bright thermal sources of keV line radiation (e.g. Al He-α resonance line [$1s^2$-$1s2p^1P$] at 1.6keV) with conversion efficiencies from optical photons of ~ 4% [1]. Thermal x-rays

are emitted isotropically with the duration of the emission limited by the plasma cooling time which can be as short as 10ps but is typically much longer [2]. When used with target materials such as liquid drops, gas jets and jets of atomic clusters the high rep rate of these systems make them attractive as high average brightness and debris-free sources useful, for example, in high-resolution lithography [3]. In addition to lithographic applications multi-keV thermal x-rays have been routinely used to backlight laser-plasmas giving diagnostic evidence of plasma evolution and providing a test-bed for theoretical studies [4].

The intensity of the radiation generated from thermal electrons may be optically thin or modified by re-absorption. In the limit of high opacity, the emission becomes that of a Planckian blackbody. The high opacity regime may be accessed with high energy lasers, were it is possible to heat large volumes to high temperature and moderate density in enclosed geometries thereby opening up a class of brighter line radiation sources at multi-keV photon energies [5]. Simulations suggest, for example, that this regime may be reached using a cylindrical beryllium container filled a low density Ge gas which is optically pumped by the kJ output from the proposed NIF laser. The resulting high brightness source is expected to deliver 3.8J at ~6.2 keV into 4π which may be used for radiographic applications [5]. Planckian continua at temperatures up to about 250eV have been produced in high-Z hohlraums irradiated by high-energy lasers in fusion research [6]. These continua extend to about 1keV beyond which the radiation spectrum is generally optically thin and there are no strong lines.

2.2 Non-thermal Sources

Laser produced plasmas also commonly have a minority of super-thermal electrons arising from non-linear laser plasma interactions at the critical and sub-critical density surfaces. These hot electrons penetrate deep into solid targets were they collisionally induce both Bremsstrahlung and K-α fluorescence in a manner analogous to a conventional x-ray tube. The fraction of laser energy converted to hot electrons increases with the product $I\lambda^2$ as does the hot electron temperature [7].

2.2.1 Bremsstrahlung Sources

For $I\lambda^2 > 10^{18}$ W cm^{-2} μm^2 the velocity of hot electrons becomes relativistic and they produce broadband MeV x-ray emission via multiple Coulomb collisions during transit through the target material [8]. The energy loss to bremsstrahlung scales as $\sim Z^2$ and so high Z materials are chosen for maximal x-ray output. The angular distribution of the x-ray emission reflects the energy distribution of the electrons because at relativistic energies the radiation is into a cone angle of $1/\gamma$, where is γ is the ratio of the rest energy of the electron to its accelerated energy [9]. Using the petawatt (PW) output of the NOVA laser, 1.2J of 1MeV photons ($\Delta\lambda/\lambda = 1$ MeV) where emitted into 2π in ~10ps [10] with a conversion efficiency of $\sim 4 \times 10^{-3}$.

The photon energy of the emitted radiation is sufficient to cause photo-neutron reactions within a number of secondary target materials. With the advent of high rep rate, high intensity laser systems it is envisaged that such a scheme may have commercial viability in the production of radioactive isotopes [9]. In addition these high energy x-rays may be used for radiography of high density plasmas.

2.2.2 K-alpha Fluorescence

For intermediate laser intensities ($I\lambda^2 \sim 10^{15}\text{-}10^{18}$ W cm^{-2} μm^2) accessible with table top laser systems the energies of the hot electrons are less relativistic and as they propagate through the target they may create K-shell vacancies giving rise to K-alpha radiation within the 5 –10 keV region. Emission typically occurs isotropically into two closely spaced K-α lines with conversion efficiencies from 10^{-5} to 10^{-4} and at multi-Hz repetition rates [11]. Recent work has measured K-α pulse durations of less than a picosecond [12, 13] and source sizes between 20-100μm [7]. The transit time and lateral movement of hot electrons within the target and the re-incidence of initially ejected electrons limit the pulse duration. For most efficient collisional creation of K-shell vacancies the hot electron temperature should be 5 to 10x the K-α photon energy. K-α line emission, pumped by a table top ultra short pulse (USP) laser system delivering energies of 0.1 to 1J per pulse, has been used recently to give single pulse time resolved measurements on lattice deformations within a laser-heated crystal sample [11].

K-α sources can be operated at high rep rates and their time averaged brightness is comparable to bending magnets at synchrotron radiation sources for lasers with average power of ~0.1 W. Technology development is rapid and 100W or even 1kW high rep rate laser systems are foreseeable and would give these sources an intermediate brightness between that of a bending magnet and an undulator with the capability of a wide range of average power applications. These sources are complemented for applications requiring a continuum spectrum, by non-thermal Bremsstrahlung sources.

2.3 High Harmonic Generation

Sources of high harmonics can deliver multiple wavelength, individually monochromatic ($\Delta\lambda/\lambda \sim 10^{-2}$) within sub-picosecond, low divergent (~ 5mrad) pulses with quasi-tunability and potential high rep rates. Harmonic emission may be generated from gaseous or solid targets.

2.3.1 Gas Harmonics

When an intense laser (~10^{15} W/cm^2) is focussed into a gas jet non-linear processes may result in high harmonics of the laser frequency being emitted within the cone angle of the laser. An electron moving in the electric field of the laser driver oscillates around the atom at a distance proportional to λ_o^{-2} (the central wavelength of the laser driver). Each time the oscillation electron comes in contact with the atom there is a probability of a harmonic photon being emitted. Currently non-phased matched gas harmonics are observed in the 10-40 eV range with typical conversion efficiencies of ~10^{-6} (~0.7µJ pulse^{-1}) [17] and in the 40-150eV range with conversion efficiencies of 10^{-8} (~1nJ pulse^{-1}) [15]. These sources have been shown to operate at kHz repetition rates down to 27Å (with 100 photons pulse^{-1}) [18]. Pulse widths of <2fs have been reported in isolated x-ray pulses with future developments in laser driver technology expected to extend the harmonic duration into the attosecond regime [19]. Systems can be compact, inexpensive and laboratory based. Recently a significant advance in HHG has been made with the report of phase-matched harmonic conversion of visible light into x-rays demonstrated within a fibre waveguide, offering a $10^2 - 10^3$ increase in efficiency over the non-phase matched case [20]. More optical laser-fiber coupling, larger diameter fibres (less absorption losses), lower absorption gases and reduced pulse duration is expected to further increase the efficiency of the *phase-matched* harmonic conversion process. Optimisation of the experimental conditions are predicted to yield milliwatts of power per harmonic peak whilst also reducing the output wavelength [21].

High harmonic generation in gaseous media is more efficient for shorter wavelength drivers as the electron spends more time in the vicinity of the parent atom [15]. The maximum harmonic energy obtainable is given by ($E_i + 3.17\ E_P$), where E_i is the ionisation energy and E_P is the time averaged pondermotive energy of an electron oscillating in an electric field and has a λ_o^2 scaling with laser wavelength. One way to extend the harmonic cut-off energy is by using ions instead of neutrals. Ions produce higher energy harmonics due to their increased ionisation potential and higher pondermotive energy. However, free electrons decrease coherence length, degrade laser beam quality and make phase matching more difficult. Preston *et al.* [16] successfully extended the maximum harmonic energy using the 249nm output of the KrF laser by using He$^+$, Ne$^+$ and He^{2+} ions.

2.3.2 Solid Target Harmonics

In solid targets odd and even harmonics are generated. This can be understood as reflection of fundamental light off an oscillating critical density surface. This "oscillating mirror" is caused by the oscillation of electrons through a steep density gradient with obliquely incident p-polarised light. Peak brightness's of between 5x10^{22} and 3.6x10^{20} brightness units have been achieved in the 10-80eV photon energy range (see figure 1). The conversion efficiency from optical to high energy harmonic photons (~10^{-6}) is proportional to $I\lambda^2$ [22] and is maximised for density scale lengths $L/\lambda \sim 0.2-0.5$ [23]. The peak brightness in this scheme in further enhanced in the absence of a preplasma due to the reduction in the relative spectral bandwidth ($\Delta\lambda/\lambda$) [24]. Laser pulse widths > 500fs generate a preplasma from the interaction of the leading edge of the pulse with the initial solid density target. In this regime, and at high intensities, hole-boring and rippling of the critical density surface causes diffuse emission of the harmonic output [25, 26], thereby limiting the peak brightness.

Advances in this scheme are dependent on the advent of high intensity (> 10^{19}), high contrast (~10^{10}) and short pulse (< 200fs) laser systems. The reduced pulse width minimises hydrodynamic expansion and the resultant small density scales lengths limits the harmonic emission to the cone angle of the laser [22, 27]. Following conversion efficiency scans with laser intensity [25], PIC simulations were carried out which predict [28] harmonic generation into the 2.33-4.36 nm

water window with the 62nd harmonic of the 249nm KrF laser with intensities of $\sim 10^{20}$ W/cm^2 on target. This wavelength range is important for biological imaging applications as it represents the spectral interval between the carbon and oxygen K-absorption edges. Such high harmonic predictions [22] are shown in figure 1, and if achieved, they promise output peak brightness's on a par with x-ray lasers in the 30-280eV photon energy range.

2.4 X-ray Lasers

Saturated x-ray laser operation has been observed at wavelengths in the 20 to 220eV range with pulse widths between 2 and 800ps. Narrow fractional bandwidth ($\Delta\lambda/\lambda \sim 10^{-4}$ Å), conversion efficiencies of $\sim 10^{-6}$, low divergence ($\sim$mrad) and high saturation intensity ($\sim 10^{11}$ W/cm^2) are characteristic of the x-ray laser output which make it the highest brightness single pulse source of x-rays currently available. An overview of the characteristics of the different x-ray laser schemes is presented below with relative comparisons shown in the brightness charts.

2.4.1 Collisional X-ray Lasers

Collisional x-ray lasers typically operate in single/double pass, high gain (~ 10cm^{-1}), amplified spontaneous emission (ASE) mode where the gain region is an extended plasma column. Population inversion is achieved by collisional excitation of the lasing ion by free electrons. In this scheme an optical laser (e.g. $\Delta t \sim 75$-100ps, 120J) is incident onto a slab target of the lasing material in a line focus geometry. Under the optimal pumping conditions a column of plasma gain medium is generated in which the x-ray photons which traverse axially have the greatest amplification. A quasi-steady state population inversion is maintained for ~ 50ps until the optimum temperature and density conditions are lost due to plasma expansion. In recent years multiple pump pumping and refraction compensating techniques have extended saturated operation of this scheme down to wavelengths as low as 58Å [30] (Ni-like Dy). High saturation intensities ($\sim 10^{11}$ W/cm^2), small source sizes (50 x 80μm) and narrow angular divergence (~ 3mrad) within a ~ 50ps pulse contribute to the high brightness output [31]. However, due to the inherent inefficiencies in this scheme, stemming from the need to over ionise the plasma in order to optimise the collisional pumping rates [32], large scale laser facilities are required to obtain saturated output. As a consequence, they have inherently low repetition rates (1 shot/20 mins) and require a large capital investment. In addition, collisionally pumped x-ray lasers scale poorly to lower wavelengths with the lowest achievable wavelength predicted to be 24 Å (Ni-like U). The mJ output of the Ne-like Ge x-ray laser at 196Å has been used as a high density probe beam in a series of radiography experiments to measure the growth of hydrodynamic perturbation in a laser ablated foil target [33]. In another recent experiment, the coherence properties of the Ne-like Zn x-ray laser at 212Å has been used in conjunction with a Fresnel bi-mirror interferometer to map the surface of a stressed Nb with $\sim$nm resolutions [34].

2.4.2 Transient Collisional Excitation (TCE)

Within the quasi steady state (QSS) scheme, the main heating pulse is used to generate a large population of the lasing ion species and also to collisionally pump the population inversion on a time scale, long, relative to the lifetimes of the lasing levels. The TCE approach is an extension of the QSS scheme in which two pulses instead of one are used to achieve the optimum lasing conditions but crucially the main electron heating occurs on a time scale shorter than the relaxation time of the lasing levels. The time scale in which this population inversion is generated is less than the time it takes for ionisation to occur and thereby more efficient use is made of the pumping laser energy. The net effect is that saturation of the x-ray laser in the transient scheme can be achieved at a fraction of the pump energy (~ 5J) with x-ray yields of up to 100μJ in 2ps [36]. The laser systems needed to provide these energies are readily available in table top dimensions. Due to the reduced size of the amplifiers the shots rate is much improved to ~ 1 shot/4 min and at a much reduced cost per shot. Saturation in the transient scheme has been reported down to 73Å in Ni-like Sm [37] with measured durations of ~ 2ps [38]. Further optimisation is expected to deliver saturated lasing output of below 100Å with less than a joule of laser energy on target. The compactness of such a system will increase the availability of the x-ray laser to the wider scientific community thus enabling research activities to move more from source development to potential applications.

2.4.3 Fast Capilliary Discharge (FCD)

Magnetic fields caused by a high current (~ 40kA) electrical pulse compresses pre-ionised gas within a Teflon capillary generating a hot dense plasma for single/double pass x-ray lasing. The gain medium has been extended to lengths of ~ 40cm giving plasma column aspect ratios of ~ 1000 with excellent axial uniformity [39, 40]. This device has table top dimensions and yields saturated operation at 469Å in Ne-like Ar (0.88J/pulse) at 7Hz giving it a high average power of

~3.4 mW [41]. The FCD x-ray laser is measured to have a peak power of the spatially coherent radiation of ~2.3 kW which exceeds by more than 5 orders of magnitude that of an undulators, estimated at 4mW [42, 43]. Lasing at 60.8nm in Ne-like S has also been reported with a gain-length product of ~7 [44]. These sources have a relatively long output pulse duration of ~0.8ns and have not achieved saturation at wavelengths below 469Å. A higher power capillary discharge system capable of delivering 200kA into 10ns has been recently developed with the expectation of generating plasma conditions required for lasing at lower wavelengths [39]. Recent work has demonstrated lasing on the J = 0-1 4p-4s transition in Ni-like Cd at 131.5nm [41]. The reported source diameter for the gain region is 300μm whilst the coherent source size has been reported to be 60μm [40]. The former figure has been used in calculating the peak and average brightness (figures 1 and 3). Expected future development of the FCD [45] x-ray laser is reflected in the brightness charts by an error bar.

A new scheme has been proposed [46] in which the capillary discharge preformed plasma combined with the transient collisional pumping by a high intensity picosecond laser may realise the benefits of both schemes.

2.4.4 Recombination
Recombination pumping of x-ray lasers has been demonstrated in H-like and Li-like [47] ions although a serious limitation is that gain saturation on a laser transition has not been demonstarted. The predicted saturation intensity for the H-like C laser is ~2x10^9 W/cm^2 which equates to an output energy of 200nJ in 50ps. This is much less than the achievable intensities of the collisional excitation schemes although the recombination schemes is expected to scale better to shorter wavelengths. With the advent of short pulse high intensity drivers there is renewed interest in the recombination scheme [48].

2.4.5 Optical Field Ionisation (OFI)
OFI schemes use the high electric fields of ultra short pulse (USP) systems to remove electrons from the atom in a short time. Pumping into the upper lasing level can occur either via collisional excitation or fast recombination. Saturated output has been obtained recently on the 5f-5d transition in Pd-like Xe (418Å) and in Ni-like Kr (328Å) [49] with a system of table top dimensions. The low energy input of the scheme allows for high repetition rates to be used with table top systems. Lasing in this scheme has also been reported within a capillary on the H-like B 3-2 line at 236Å [50]. Predicted low saturation intensities (~10^7-10^8 W/cm^2) and short durations are characteristic of the OFI x-ray laser output. It is not possible to scale this laser scheme below 50Å due to collective heating effects (e.g. Raman heating) that would arise from increased pumping intensities. With the advent of TCE x-ray lasers which have shown saturated operation down to 140Å with table-top dimensions (and potential high rep rates) the attractiveness of the OFI schemes has diminished.

2.4.6 Inner Shell Photo-Ionisation (ISPI)
There has been interest for many years in generating gain on inner shell transitions but to date no experimental demonstration has been made. Theoretical work by Moon and Eder [51] suggests that lasing on the inner shell transition in Carbon at 45Å is possible with the availability of a pumping laser able to deliver 1J in 45fs. Outputs of ~ 0.1μJ in > 100fs at 7Hz are expected. Simulations on the inner shell transition for for Ne (λ ~14.6 Å) [52] predict gain of 10cm^{-1} with a saturation intensity of 10^{15} W/cm^2. With predicted gain lifetimes of ~60fs (due to fast non-radiative Auger decay) it is necessary to provide selective pumping of the inner shell transitions in a precise travelling wave geometry. The pumping of inner shell transitions can be achieved by one of two methods. A relativistic beam of electrons, generated by high intensity laser radiation (Iλ^2 > 10^{18} W cm^{-2} μm^2), may be used as a travelling wave pump source of hard x-rays. Such a proposed experimental design is described by Fill *et al.* [53]. Alternatively filtered thermal emission from a plasma with radiation temperature ~500eV may be used. These hard x-rays are used to photo-ionise inner shell electrons and so produce population inversion on inner shell transitions. Work currently underway at LLNL with the FALCON laser is expected to provide an output at 45Å for the inner shell transition in C with 10μJ in 60fs from an estimated source size of 1x10^{-4} mm^2 and a divergence of 1mrad suggesting a peak brightness of 4x10^{28} brightness units [54]. The predicted figures for the brightness of the C inner shell x-ray laser is shown in figure 1.

2.5 Thomson Scattering of relativistic electron beams

The advent of very low emittance ~MeV electron beams based on laser photocathode electron sources and RF accelerators in has made possible effcient interactions between focussed relativistic e-beams and focussed laser pulses with densities of photons and electrons sufficient to produce usefully intense x-rays in well collimated beams.

In a recent experiment, high energy x-rays (~30keV) were generated from 90° Thomson scattering between a 100fs TW laser pulse and highly relativistic (50MeV) electrons from an accelerator [55]. The periodic undulating magnetic field of the laser photons translated to the rest frame of the electrons is close to a plane wave. As the electrons are undulated in the magnetic field of the laser they emit photons which are scattered in the forward direction and have a central wavelength of the undulating period (λ_{Laser}) relativistically contracted to the laboratory rest frame. Reported outputs of 5×10^4 photons pulse^{-1} at 30keV have been observed in a 300fs pulse at a 2Hz repetition rate within a 15% fractional bandwidth. The duration of the scattered x-rays is determined by the transit time of the laser through the electron pulse. The x-ray photons can be tuned by varying the photon energy, the electron beam energy or the scattering angle. By increasing the laser pulse energy and improving the compression of the electron pulse a six order of magnitude increase in the scattered x-ray brightness is proposed [55].

2.6 Larmor radiation

Theoretical predictions [56] suggest that Larmor radiation has interesting possibilities as an x-ray source in conjunction with modern high intensity high repetition rate ultra short pulse lasers. Larmor radiation is simply the limiting case of Thomson scattering from free electrons when the electron motion becomes strongly relativistic. The total Thomson scattered power is conserved in the relativistic transformation but the increased angular concentration into a narrow beam and the upshifted frequency create the potential for a bright x-ray source. There have been no experiments to date measuring Larmor radiation in the x-ray region but the onset of non linear behaviour in Thomson scattering has been verified at lower intensities.

The expected brightness of Larmor radiation is shown in figure 1 where it is apparent that if obtained it would be superior to other sources in the 10 keV region. Some cravats apply here because theoretical estimates are compared with experimental results for other sources and there are clearly some factors which will reduce the brightness of Larmor emission. The assumption of near critical density of electrons over a Rayleigh length is optimistic because relativistic self-focussing modifies the interaction length

A proposed method for producing enhanced Larmor radiation involves the insertion of a thin film between two counter propagating laser beams. The first laser interacts with the foil and generates relativistic (MeV) electrons. The foil should be sufficiently thick to transmit the electrons but absorb the laser light. The second beam travelling in the opposite direction encounters the electrons and oscillates their trajectory thereby initiating emission of energetic photons. In this scheme it is predicted that by using 2 x 2PW lasers 1MeV photons can be generated with an intensity of up to 3.2×10^{18} W/cm^2 [56].

3. COMPARITIVE STUDY OF LASER BASED SOURCES

A summary of the peak brightness for each of the laser based x-ray sources discussed is shown in figure one. Experimentally measured data is shown by the solid data points with expected near-future developments represented by an error bar. Proposed but currently unobserved sources are shown with the open data points. Collisional excitation x-ray lasers are seen to be the highest peak brightness source of x-rays due to their high collimation, high pulse energy and their narrow fractional spectral bandwidth. They are however not expected to scale to wavelengths below 24Å and so for applications requiring higher photon energies other sources become more important. Line radiation from thermal and non-thermal K-α sources are seen to approach the limit of the Planckian curve (T_e − 1.5keV) which is shown for illustrative purposes. Currently realised sources of gas and solid harmonics have lower peak brightness's than the x-ray laser reflecting their they inherent greater divergence and spectral bandwidth of these schemes. An exception this is shown be the recent generation of phased matched gas harmonics (at 38.75eV) which improves the brightness of gas harmonics by two orders of magnitude. Gas harmonics have an important advantage over x-ray lasers due to the small dimensions of the systems allows them to be operated at high repetition rates. The only exception here is the fast

capillary discharge x-ray laser which can operate at 7Hz and so has a high average brightness. For the high energy sources only Thomson, Bremsstrahlung and potentially Larmor sources have partial collimation.
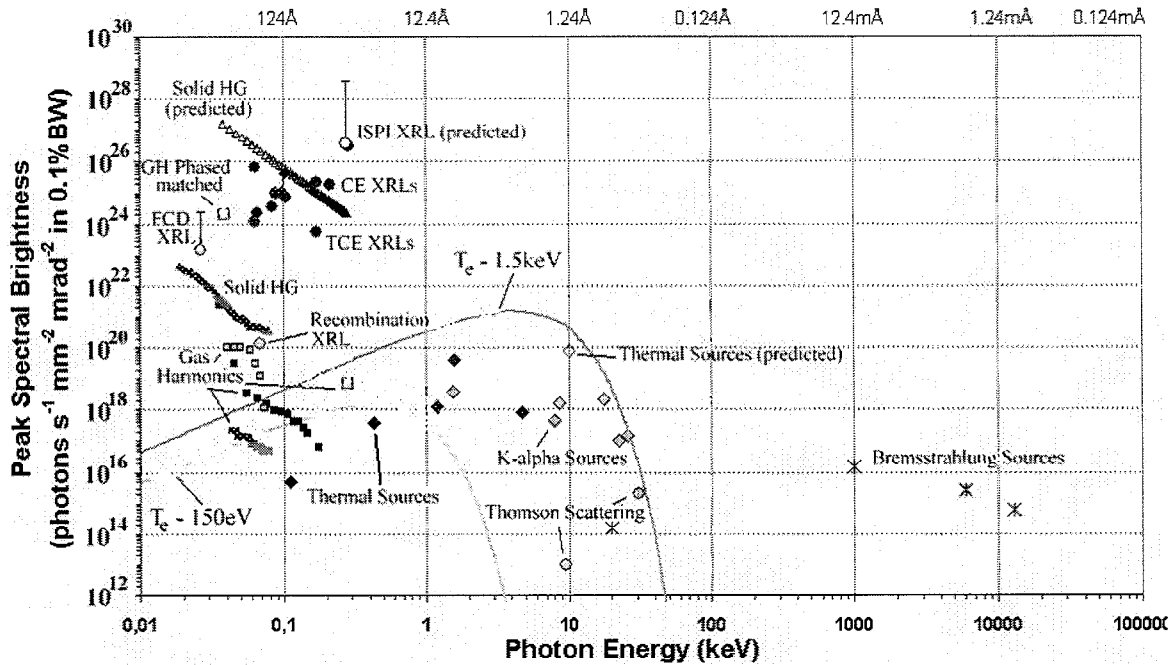

Figure 1: Peak Brightness for a host of Laser based x-ray sources. All sources are currently realised unless otherwise stated. CE XRL : Collisional Excitation X-ray Lasers; TCE XRL : Transient Collisional Excitation X-ray Lasers; FCD XRL: Fast Capillary Discharge X-ray Laser; GH : Gas Harmonics; ISPI XRL : Inner Shell Photo-Ionisation X-ray Laser; HG : Harmonic Generation. Error bars are shown to indicate expected near term improvements in performance.

4. COMPARITIVE PEAK AND AVERAGE SPECTRAL BRILLIANCE OF SYNCHROTRON BASED X-RAY SOURCES

The peak brightness for a host of synchrotron based sources of x-rays is shown in figure 2. Experimentally realised figures for the Advanced Light Source (ALS) and the Advanced Photon Source (APS) [57] are shown alongside, for comparison, the peak brightness of the collisional excitation x-ray laser. Also shown in the plot are the predicted outputs from the proposed x-ray FEL facilities in the USA (SLAC) [58] and in Germany (DESY and TESLA) [59]. It may be seen from this graph that the x-ray laser is the highest brightness single pulse source of x-ray radiation currently available. However with the SLAC facility expected to be operation in 2005 the peak brightness of the x-ray laser may be exceeded by up to ten orders of magnitude. It may be seen that even if the output of the SLAC FEL fails to add coherently as predicted the brightness of the spontaneous emission still surpassed that of the x-ray laser. In figure 3, a summary of the average brightness of synchrotron based light sources is presented. As in figure two the predicted outputs from a number of X-ray FEL facilities are shown. For comparison, the average brightness of the 7Hz fast capillary discharge x-ray laser [39] is shown along with a 300Hz laser-plasma thermal source [1]. The error bar for the FCD x-ray laser reflects expected improvements in output [45]. Synchrotron sources offer good average brightness over a large spectral range and near term improvements are expected with the development of FEL facilities.
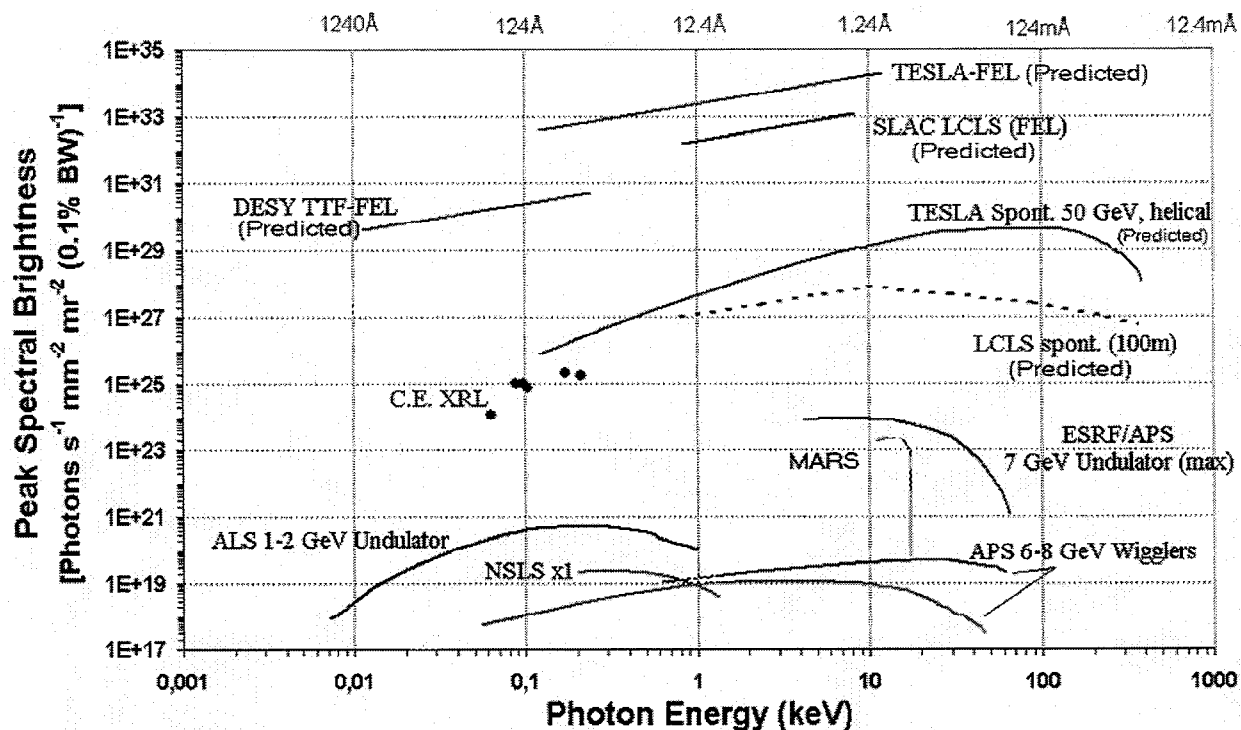
Figure 2 : Peak brightness for existing and predicted Synchrotron based sources with brightness associated with collisional excitation pumped x-ray lasers (C.E. XRL) shown for comparison.
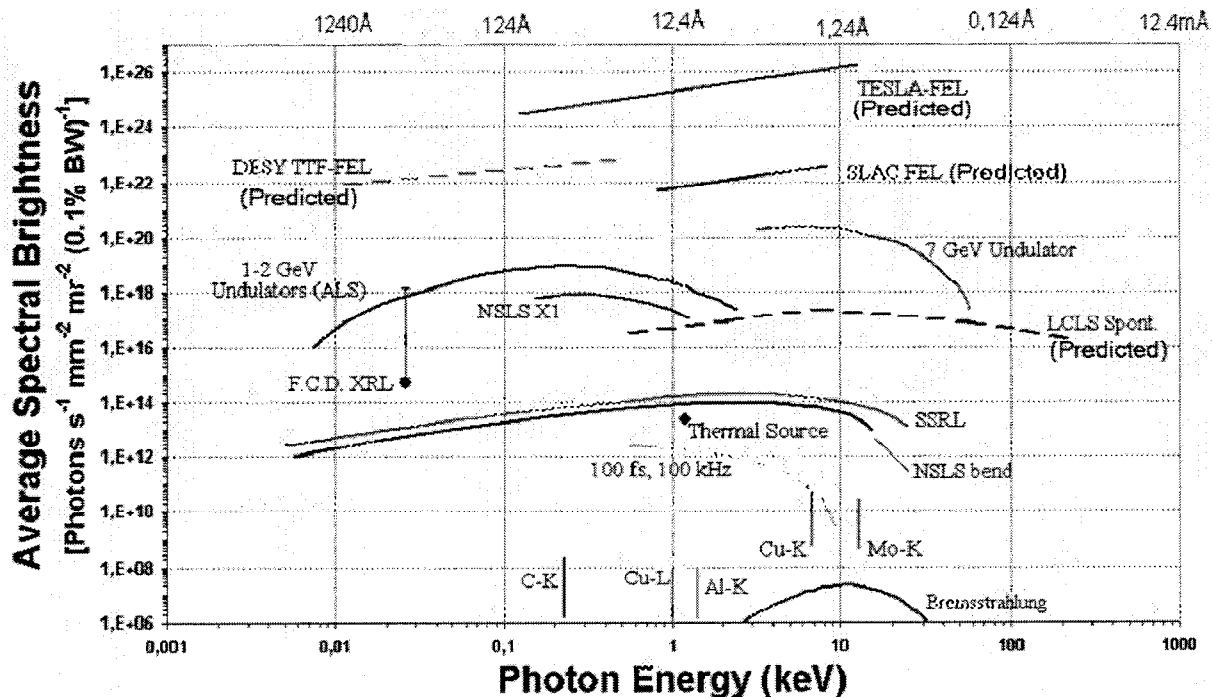

Figure 3: Average Brightness for existing and predicted Synchrotron based sources. The average brightness associated with the Fast Capillary Discharge x-ray laser (F.C.D. XRL) along with that of laser based thermal sources is shown for comparison. The error bar associated with the x-ray laser data point represent expected near term enhancements in performance.

5. CONCLUSIONS

Femtosecond x-ray pulses are potentially important for a wide range of applications as discussed within this paper. Laser based sources can be laboratory sized with high rep rates and x-ray pulses down to a few fs.Future development here is largely dependent on the advent of short pulse, high intensity, large contrast ratio laser drivers.Currently x-ray lasers are the brightest single pulse source of x-rays however with the advent of FEL's this figure could be surpassed by up to 10 orders of magnitude.

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